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CHANNEL CHANGES DUE TO RIVER REGULATION: THE CASE OF THE PIAVE RIVER, ITALY

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ABSTRACT

This paper deals with the channel changes of the Piave River in the Eastern Alps, Italy, which have occurred during this century in response to human interventions in the fluvial system. The flow regime and the sediment supply of the river have been considerably altered by hydroelectric dams, flow diversions and gravel mining. In addition, river dynamics have been affected by the construction of streambank protection structures. To document these changes, a historical analysis was performed using maps and aerial photographs. Morphological features that were examined included planform configuration, channel width, braiding index and bed elevation. The results indicate that as a consequence of decreases in the flows and sediment supply, remarkable channel changes have occurred in the river during this century, especially during recent decades. The channel has undergone a general narrowing with a decrease in average width to 35 per cent of its initial value, while the braiding index has decreased from about 3 to 1·5. In several reaches the planform pattern has changed from braided to wandering. The observed trends of channel change suggest that the river has not yet reached a new equilibrium condition and it may, therefore, be predicted that reductions in width and braiding intensity are likely to continue in the immediate future. Copyright © 1999 John Wiley & Sons, Ltd.

KEY WORDS: channel changes; braided river; channel width; braiding index; channel forming discharge; human impact; Piave River; Italy

INTRODUCTION

In numerous catchments throughout the world human intervention has strongly altered natural river dynamics, especially in recent decades. Dams and reservoirs constructed to generate hydroelectric power, flow diversions and gravel mining constitute the most common forms of intervention in fluvial systems, and each causes substantial changes to the flow and sediment regimes. The response of flow processes and channel morphology to engineering and regulation of alluvial streams have been studied widely (e.g. Gregory and Park, 1974; Petts, 1977; Williams, 1978; Castiglioni and Pellegrini, 1981; Williams and Wolman, 1984; Andrews, 1986; Knighton, 1989; Dutto and Maraga, 1994; Petit *et al.*, 1996; Billi and Rinaldi, 1997; Kondolf, 1997). The results of these studies not only demonstrate that process–response may generate remarkable channel changes, but also show that the modes of change and response times vary considerably from one stream to another.

This paper examines the channel morphology of the Piave River in the Eastern Alps, Italy, and, in particular, changes that have occurred during this century in response to increasing human impacts on the river. Documentation of these changes is useful in three ways. First, it allows relationships between the control variables (discharge and sediment load) and the response variables (channel characteristics) to be explored. Second, it supports evaluation of the effects of human intervention on channel morphology. Third, it provides the basis for prediction of the future evolution of the river.

Uses of the Piave River are multifunctional and, inevitably, management issues surrounding the river are complex. Major issues are directly related to water resource management, hazard mitigation, mineral extraction and environmental conservation. Water issues centre on use of the river for hydroelectric power

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and water abstraction, from both the river and basin aquifers, for irrigation and domestic supply. Hazard management involves works constructed for flood defence. Mineral extraction takes place primarily through gravel mining, with implications for the supply of sediments to the coast. Environmental issues tend to focus on protecting and enhancing ecosystems in the riparian corridor. However, it is now generally recognized that hydraulic and ecological studies alone are insufficient to support best practice in environmental conservation and that geomorphic understanding of channel form and evolution is also essential. This is the case because application of geomorphic principles and insights allows managers to assess the effects of human influence on the fluvial system and to mitigate those effects in situations where they result in substantial alteration of natural processes, loss of natural capital or increased risk to people or ecosystems.

REGIONAL SETTING

The river and study reach

The Piave River rises at an elevation of 2037 m a.s.l. and has a length of 222 km. It flows from its source in the Dolomites, via the Venetian Pre-Alps, to Nervesa, at 80 m a.s.l., where it enters the Venetian Plain (Figure 1). Its mouth, in the Adriatic Sea, is located about 30 km northeast of Venice. The drainage basin is mainly composed of sedimentary rocks (predominantly limestone and dolomite) and has an area of 3899 km^2. Morphologically, the course of the river can be divided into three reaches. The upper course, where the river is generally incised in the bedrock and therefore has a quite narrow channel, extends from the source to Longarone. The middle course, where the river is very wide and characterized by a multithreaded channel pattern, extends from Longarone to Ponte di Piave. The lower course, where the river meanders but has been artificially straightened in places, extends from Ponte di Piave to the mouth.

Channel response to human activities has been investigated in the middle course in this study because changes there have been substantial and are amenable to analysis using historical maps and aerial photographs. In the 110 km of its middle course the river is several hundred metres wide, with a multithread planform pattern, a predominantly gravel bed and a gradient ranging between 0·003 and 0·006.

Geomorphological evolution during the Lateglacial–Holocene

To understand the dynamics of the Piave River during this century, it is useful to examine its longer-term evolution. The present physiographic setting of the river results mainly from drainage system evolution during the Lateglacial and the Holocene. Following retreat of the Würmian glacier, around 15 500–16 000 years BP, a phase of valley aggradation occurred. Surian (1996) established that this phase lasted up to 8000–9000 years BP in the Vallone Bellunese, between Soverzene and Busche, but there are no precise chronological data for other reaches. After this period of aggradation, the river in the Vallone Bellunese began to incise into the deposits, to form a series of terraces. According to this evolution model, two main phases (aggradation followed by incision) occurred in the river between Longarone and Nervesa, whereas in the downstream reach aggradation prevailed throughout the Holocene. A large fan, with its apex at Nervesa, developed during this period and it has remained active up to historical times. However, since the 14th century AD, engineers have worked to canalize the river at the apex of the fan, to stabilize its course and constrain flow within the main channel during major floods (Vollo, 1942).

STUDY METHODS AND SOURCES

The evolution of the Piave River during the last century has been analysed on the basis of hydrologic data, historical information on channel morphology, and records of human intervention in the natural operation of fluvial system.

Many researchers have found historical maps and aerial photographs to be very useful tools for the analysis of channel changes (Castiglioni and Pellegrini, 1981; Bravard and Bethemont, 1989; Hooke and Redmond, 1989; Castaldini and Piacente, 1995). In the case of the Piave River, historical analysis is particularly

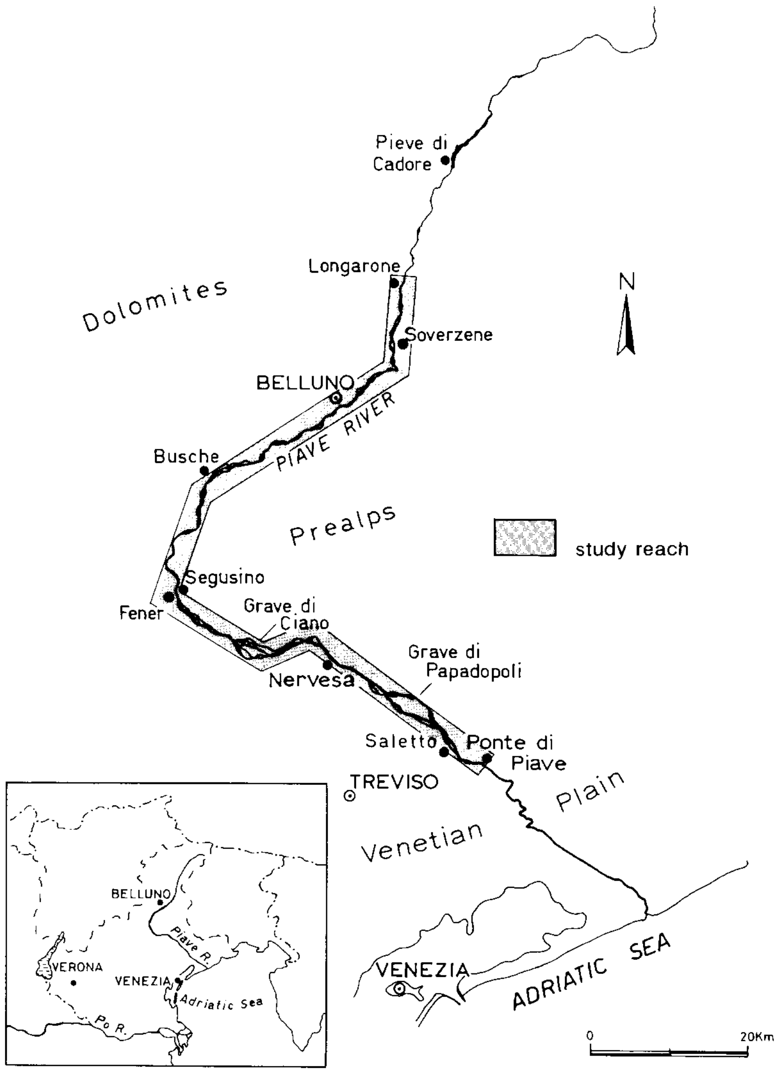

Figure 1. Location map of the Piave River and study reach

appropriate due to the availability of high quality, large-scale maps over a long period of time. Also, the middle reach of the Piave River is well suited to this type of morphological analysis due to its large size and because its braided planform means that morphological changes are clearly displayed in maps and aerial photographs.

The maps used in the analysis included the map of Regno Lombardo-Veneto, different editions of the maps of Istituto Geografico Militare Italiano (IGMI), and the Carta Tecnica Regionale (CTR). The map of Regno Lombardo-Veneto was published in 1833 and its scale is 1:86 400. The IGMI maps have a scale of 1:25 000 and there are different editions (commonly four or five, it varies from one sheet to another) starting from the end of the 19th century up to the 1960s. The CTR maps, at a scale of 1:10 000, are based on aerial photographs taken between 1980 and 1983.

In this study, the Regno Lombardo-Veneto, though a very accurate map, was used only qualitatively, owing to its small scale. However, quantitative analyses were performed on the more recent maps. More recent information was derived from aerial photographs taken in 1990 and 1991, at an average scale of

Table I. Dams on the Piave River and its tributaries. Note that the list also includes two river barrages (Soverzene and Busche) (data from SADE, 1960; ENEL, 1991, 1993)

River	Dam	Drainage area upstream from dam (km^2)	Year of dam closure
Tesa Creek – Rai River	S. Croce	136	1929
Piave River	Soverzene	1690	1929
Ansiei Creek	S. Caterina	255	1931
Piave River	Comelico	362	1931
Cordevole Creek	Ghirlo	419	1939
Piave River	Pieve di Cadore	818	1949
Boite Creek	Valle di Cadore	380	1950
Gallina Creek	Val Gallina	14	1951
Caorame Creek	La Stua	28	1954
Maé Creek	Pontesei	151	1955
Boite Creek	Vodo	323	1958
Vajont Creek	Vajont	62	1958
Piave River	Busche	3174	1960
Mis Creek	Mis	108	1964

1:20 000. Morphological attributes measured or examined on the maps and aerial photographs included channel width, planform configuration, braiding index and bed elevation.

HUMAN INTERVENTION IN THE FLUVIAL SYSTEM

Dams and diversions

Flow in the Piave River has been regulated for irrigation and hydroelectric power generation over a long period. The first important diversions for irrigation date to the 15th century, when flows were diverted at Pederobba and Nervesa. At the beginning of this century, an average discharge of 9–20 $m^3\ s^{-1}$ was diverted by the Brentella canal at Pederobba and 3–5 $m^3\ s^{-1}$ was abstracted by the Piavesella canal at Nervesa (Vollo, 1942). Natural flows of the river have been substantially modified during the last 70 years and particularly during the last 40 years. Between 1930 and the early 1960s many dams were built in the basin, both on the Piave River and its main tributaries (Table I). The volume of water diverted has increased substantially since the early 1960s, both at existing diversions, such as Soverzene, and at new diversions, such as Busche. At present a complex regulation scheme exists (Figure 2), designed to maximize production of hydroelectric power and irrigation water. The present regime of water regulation and diversion alters both the flow duration characteristics and volume of annual runoff in the river.

There are four important diversions at barrages in the study reach between Longarone and Ponte di Piave: Soverzene (mean annual discharge = 42·7 $m^3\ s^{-1}$), Busche (41·2 $m^3\ s^{-1}$), Fener (36·2 $m^3\ s^{-1}$ to the Brentella canal), and Nervesa (23·0 $m^3\ s^{-1}$ to the Piavesella canal). Considering that the mean annual discharge at Nervesa would be 132 $m^3\ s^{-1}$ under natural conditions (Tonini, 1968), it is clear that remarkable quantities of water are being diverted from the river. It should be borne in mind though that some of the diverted water returns to the river at some distance downstream. In practice, the net discharge diverted from the river upstream of Nervesa is about 87 $m^3\ s^{-1}$, which constitutes approximately two-thirds of the mean annual discharge. A total of 49 $m^3\ s^{-1}$ of the diverted flows are used for the irrigation of the High Treviso Plain, while 38 $m^3\ s^{-1}$ are carried via an inter-basin transfer to the Livenza River.

The reservoirs and diversions along the river and its tributaries also affect the supply and transport of sediment. There must have been a remarkable reduction in sediment supply to the middle course of the river because dams now trap the sediment yield from more than 50 per cent of the upstream drainage basin. Also, sediment transport through the middle course is disrupted by the barrages at Soverzene, Busche, Fener and Nervesa. Estimates of the sediment yield (Dipartimento Lavori Pubblici and PRASS, 1983; D'Alpaos and Dal

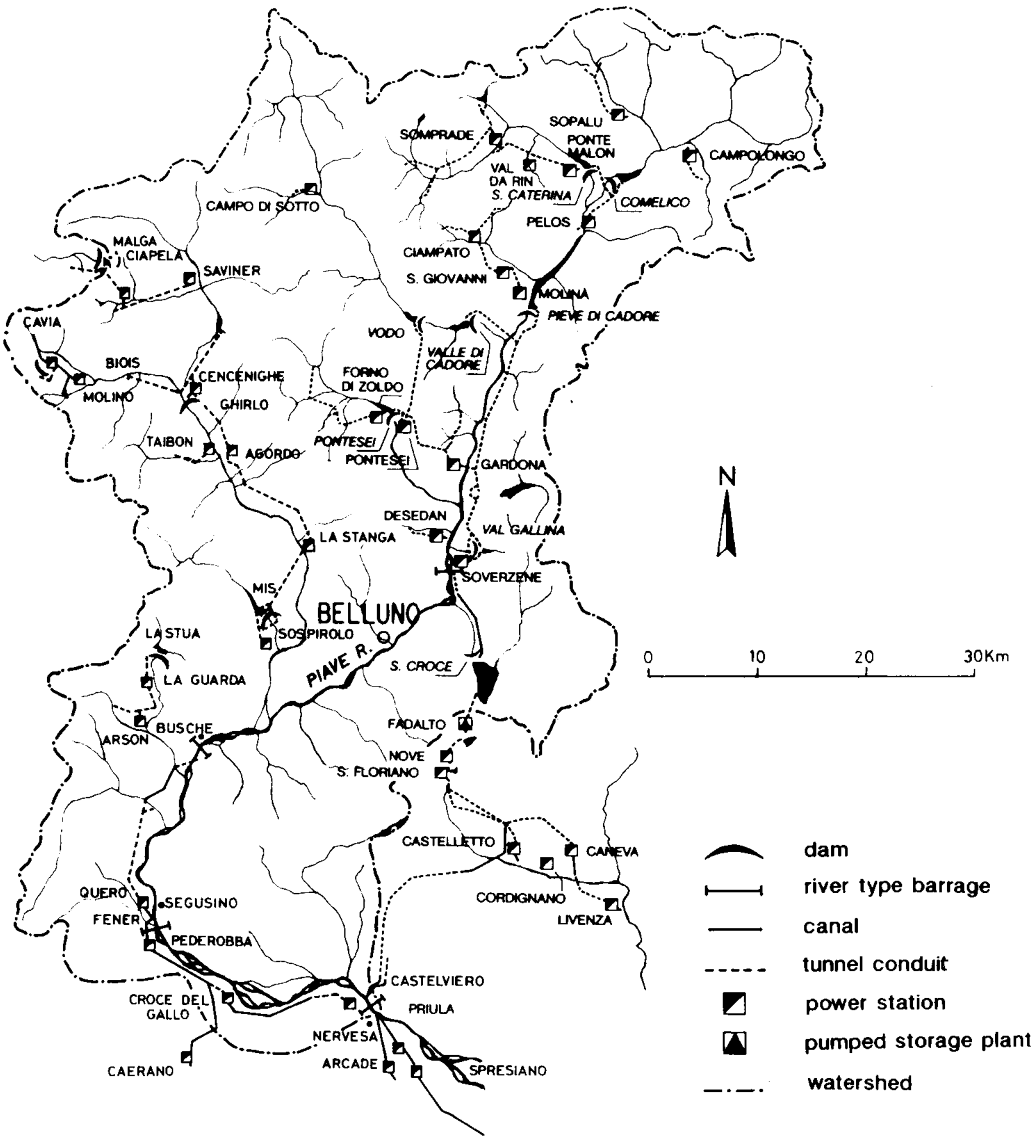

Figure 2. Water resource development in the Piave River Basin. Note the four main water diversions in the middle–lower reach of the river (Soverzene, Busche, Fener and Nervesa) and the complex network of dams, canals and power stations

Prà, 1996) vary widely and indicate great uncertainty regarding the suspended load, the bedload and the sediment delivery ratio. However, volumetric measurements of sediment trapped in the reservoirs suggest that the pre-dam sediment yield at Fener was in excess of 1×10^6 m^3 per year; today, only a fraction of this quantity, estimated at 145 000 m^3 per year, passes Fener, having not been trapped behind the dams upstream (Dipartimento Lavori Pubblici and PRASS, 1983).

Gravel mining

In addition to reductions in sediment supply due to trapping by dams, the effects of gravel mining must also be considered. Intense mining has taken place in the Piave River and in its main tributaries since the 1960s. In general, no records are kept of the volume of sediment mined from the channels but some data exist for

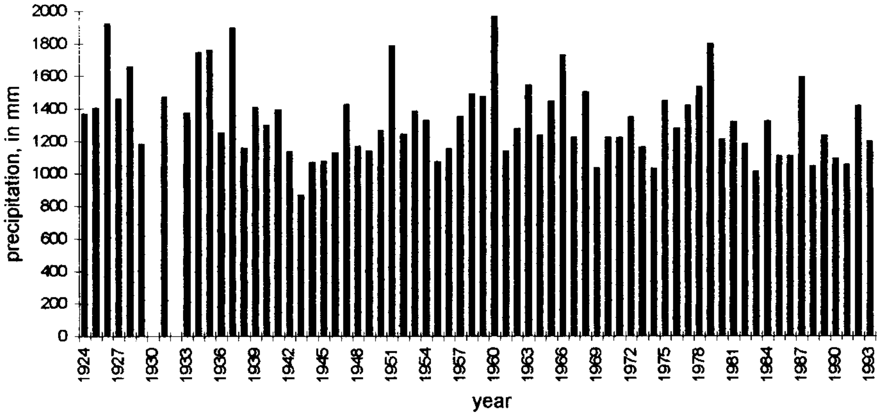

Figure 3. Mean annual precipitation in the Piave Basin upstream of Fener between 1924 and 1993

particular years and periods. Officially, 170 000 m^3 sediment was excavated from the river upstream of Fener and its main tributary (Cordevole Creek) in 1973, but this value is likely to be an underestimate (Susin, 1975). In 1993 and 1995 the volumes excavated from the main river upstream of Fener and its tributaries were 303 000 m^3 and 348 000 m^3, respectively. It is also recorded that between Fener and Nervesa, 339 000 m^3 of sediments were removed between 1990 and 1996 (D'Alpaos and Dal Prà, 1996).

Streambank protection structures

Direct effects on the morphology of the Piave River have also resulted from streambank protection structures constructed for a variety of purposes. In the upper part of the study reach, between Longarone and Nervesa, the first bank protection structures were built following the 1926 and 1928 floods (Vollo, 1942). These structures were set back from the river to create a belt at least 300 m wide, within which the river was free to shift laterally (Vollo, 1942). Since then many more groynes and levees have been built, constraining the river to maintain a narrower and less wandering channel, reducing bank erosion and giving the opportunity to cultivate some large areas abandoned by the river. In 1973 the total length of bank protection structures between Soverzene and Fener was 19 km (Susin, 1975). As a result of these bank protection works, at present the river can still move laterally, although the available width for planform shifting is narrower than its natural braid belt. Only in short reaches, for example at Longarone and Belluno, is the river channelized into a single, fixed channel by continuous structures. In the lower part of the study reach, between Nervesa and Ponte di Piave, the river has become progressively more channelized through construction of bank structures required to prevent flooding of the densely populated plain. However, these works still maintain a large channel width (several hundred metres or more).

HYDROLOGY

Precipitation

Precipitation records were assembled and examined to identify whether significant changes that might have triggered morphological response in the river had occurred in the past. Mean annual precipitation in the drainage basin upstream of Fener was evaluated for the period 1924–1993 (Figure 3). During this period, data were recorded at a large number of gauges (ranging from a minimum of 19 gauges to a maximum of 53 gauges) uniformly distributed throughout the basin. Hence, the mean annual precipitation may be calculated simply as the arithmetic average of the gauge values. The average annual precipitation for the period of

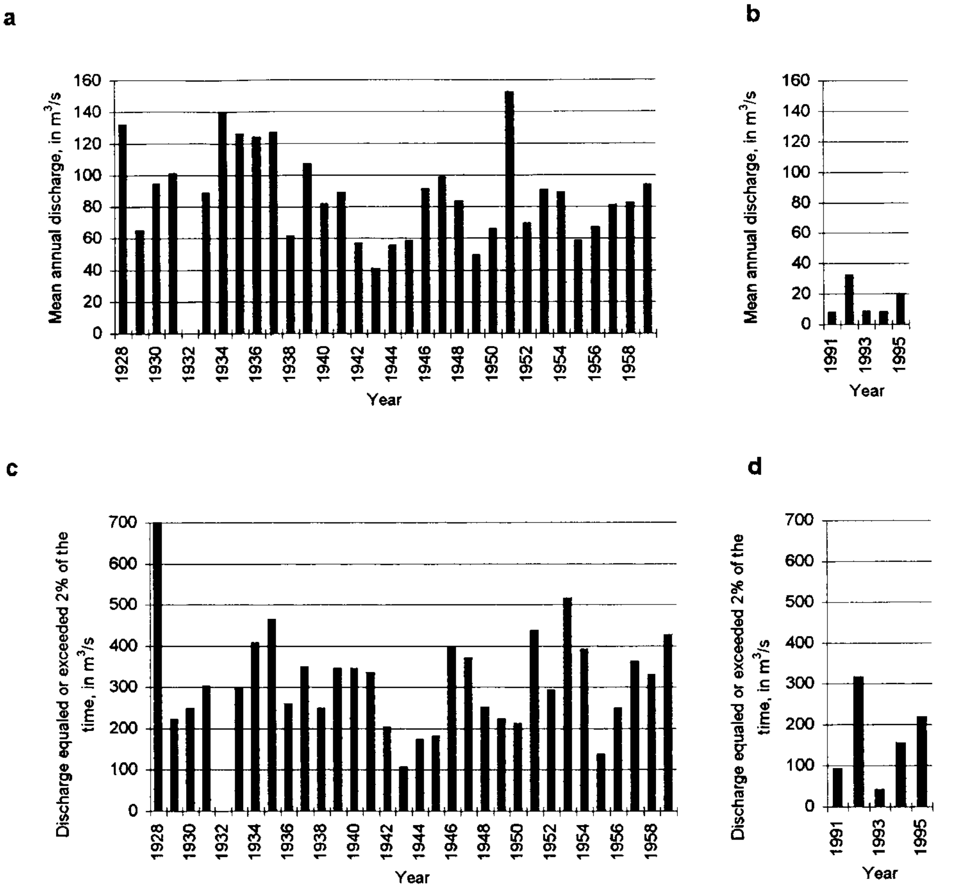

Figure 4. Flow characteristics for the Segusino (1928–1959) and Fener (1991–1995) gauging stations represented by: (a, b) mean annual flow; (c, d) discharge equalled or exceeded 2 per cent of the time

record was 1333 mm, whereas the lowest value was 867 mm (in 1943) and highest was 1965 mm (in 1960). Though there are considerable year-on-year variations of precipitation, the data do not show any significant trend that would drive systematic change in the catchment runoff regime.

River discharge

Characteristic discharges were calculated for gauging stations to identify and evaluate changes in the flow regime due to river regulation. Flow parameters computed included the mean annual discharge, annual peak flow, dominant discharge and lowest annual flow. The first three parameters were selected because they represent geomorphologically significant, or channel-forming flows. The lowest flows are significant for other reasons, including the transport and deposition of fine sediment and maintenance of in-stream and riparian ecosystems.

Unfortunately there are gaps in the flow records (Figure 4). The best series of flow data was collected at Segusino between 1928 and 1959. During this period flows were less regulated than nowadays but were not totally natural because the diversion at Soverzene was operating (average annual discharge of the

diversion = 30 m^3 s^{-1}). There are few data for the last 40 years. The Segusino gauging station was discontinued in 1959, but a complete flow series exists for the nearby Fener gauging station since 1991. Data from these two gauging stations can be compared because Fener is located only 2 km downstream of Segusino and there are no significant tributaries between the stations. Discharges at Fener are affected not only by the Soverzene diversion where, since the end of the 1950s, abstractions have increased to about 43 m^3 s^{-1}, but also by the Brentella canal diversion (36·2 m^3 s^{-1}).

At Segusino during the period 1928–1959 the mean annual flow was 87·8 m^3 s^{-1}, with a range of 40·8 to 152 m^3 s^{-1}. Annual peak flow varied between 255 and 1200 m^3 s^{-1}, with mean annual flood of 567 m^3 s^{-1}. The lowest annual flow varied between 17·9 and 40·8 m^3 s^{-1}, with an average of 27·2 m^3 s^{-1}. At Fener, the mean annual flow for 1991–1995 was 15·3 m^3 s^{-1} (range 7·8 to 32·1 m^3 s^{-1}) and the mean annual flood was 341 m^3 s^{-1} (range 156 to 575 m^3 s^{-1}). The lowest annual flow was zero in all five years and, in fact, at present the river has a discharge of only a few metres per second for many days per year.

It is clear that both mean annual flow and lowest annual flow have substantially decreased due to river regulation. The annual peak flood flow has also decreased, but to a lesser degree, while high-magnitude, low-frequency events have been unaffected. This is the case because the regulation schemes are not designed for flood control. Hence, for example, regulation had no effect on the 1966 flood, which was the highest flood during this century, with peak flow of 4250 m^3 s^{-1} at Segusino and a recurrence interval 150 years (Ghetti *et al.*, 1970).

Channel-forming discharge

Magnitude–frequency analyses of geomorphic processes (Wolman and Miller, 1960), suggest that the hydraulic geometry of many stream channels is adjusted to the discharge that transports most sediment over a long period. The discharge transporting most sediment is commonly called ‘effective’ or ‘dominant’ discharge and is often closely related to bankfull discharge. Andrews and Nankervis (1995), for instance, found a good one-to-one agreement between bankfull and effective discharges. The flow duration of bankfull or effective discharge varies as a function of the drainage area and other hydrologic and geomorphic characteristics. For example, Dunne and Leopold (1978) reported that bankfull discharge was equalled or exceeded 2·1 per cent of the time, while Andrews (1980) found that effective discharge was, on average, equalled or exceeded 1·6 per cent of the time in 15 streams with drainage areas varying between 51·8 and 9660 km^2, in Wyoming and Colorado. According to Batalla and Sala (1995), bankfull and effective discharge are equalled or exceeded 2·2 per cent of the time in a sandy, gravel-bed river in northeast Spain, with a drainage area of 114 km^2. However, effective discharge is exceeded for more of the time in rivers with very large drainage basins. For example, it is equalled or exceeded 18 per cent of the time in the Brahmaputra River, Bangladesh, which has a drainage area of 666 000 km^2 (Thorne *et al.*, 1993).

The Wolman and Miller (1960) magnitude–frequency analysis cannot be applied universally and various revisions and modifications have been recommended over the years (Lewin, 1989). A particular problem arises in application of the dominant discharge concept to arid and semi-arid regions, where the role of extreme floods is greatest, and in small catchments, where flood durations are very short (Lewin, 1989). In the case of the Piave River, floods with large magnitude and long recurrence interval do not seem to be particularly significant in forming the channel morphology. In fact, the morphological impacts of the flood of record that occurred in 1966 (recurrence interval of 150 years) had disappeared by the early 1980s due to effects of more frequent floods.

Owing to the paucity of historical flow, morphology and sediment transport data for the Piave River, it was not possible to compute effective or bankfull flows to represent the dominant discharge. However, if it is accepted that, in basins of the scale of the Piave, the effective or bankfull discharge is equalled or exceeded about 2 per cent of time, then channel-forming discharge can be approximated on this basis. The results of this exercise indicate that for the period 1928–1959 the discharge that is equalled or exceeded 2 per cent of the time ranges between 106 and 700 m^3 s^{-1} with a mean of 316 m^3 s^{-1}. For the period 1991–1995 it ranges between 42 and 317 m^3 s^{-1} with an average of 165 m^3 s^{-1} (Figure 4). Though the flow record at Fener is too short to be statistically meaningful, this finding is indicative of the degree to which river regulation has reduced channel-forming discharges in the Piave River.

CHANNEL CHARACTERISTICS

Planform configuration

The planform evolution of the Piave River is illustrated in Figures 5 and 6. The configuration of the river on different dates is shown using a sequence of pictures rather than by superposition because the braided pattern would otherwise result in a very confusing image. Figure 5 represents the river at Grave di Ciano during the last 70 years. In this reach, the river is bordered by terraces between 6 and 15 m high which delimit a braid belt, or river corridor, that is 2 to 3 km wide. In 1924 the river occupied a great portion of the area between the two scarps and it had several channels divided by vegetated and unvegetated bars. In 1967 a large vegetated island had formed in the middle part of the river and the stream flow was divided into two main branches. In the recent images (1982 and 1991) the right branch has been abandoned and the river, which is much narrower than in former times, flows only in the left branch.

The second example covers the most downstream reach studied (Figure 6). Here, the river is only slightly incised into the floodplain and groynes and levees have been built to control lateral erosion and flooding. Downstream of this reach the river changes its pattern from braiding to meandering and the channel is much narrower. As at Grave di Ciano, the sequence of images shows that major planform changes have occurred during the last 80 years. The general trend is for the channel to narrow and become less braided, but also a change in channel pattern can be detected in images for the last two dates (1983 and 1990). Especially in the reach downstream of Saletto, the river tends to form a single, more sinuous channel. This configuration may be defined as ‘wandering’, which represents an intermediate or transitional configuration between braided and meandering patterns (Church, 1983; Ferguson and Werritty, 1983; Billi, 1988; Alabyan and Chalov, 1998).

Channel width

Channel width is an important feature of river morphology that can adjust to changes in the flow regime relatively quickly, especially in a gravel-bed river with easily erodible banks. The width of the Piave River is generally free to adjust to the channel-forming flow except where it is controlled by topography or geology. A good example of topographic constraint due to narrowness of the valley floor may be found in the Busche–Fener reach, while the channel is quite narrow and more stable at Ponte nelle Alpi, Belluno, Busche and Quero, because it is incised into bedrock.

Quantitative analysis of channel width and its variation through time was performed using 94 transects extracted from historical maps and aerial photographs of the study reach at about 1 km intervals. IGMI maps (1:25 000 scale) were used to determine the width of the river from the end of the 19th century to the 1960s, while CTR maps (1:10 000 scale) were used for the period 1980–1983. The most recent situation (1990–1991) was derived from colour aerial photographs with an average scale 1:20 000. The maximum measurement error was estimated to be $\pm$ 0·5 mm, corresponding to $\pm$ 12·5 m on the 1:25 000 scale maps. This error margin is acceptable given the large width of the river and the great magnitude of observed channel changes.

Three main morphological features of the Piave River may be identified: channels, which are the lowest portions of the river bed; unvegetated or sparsely vegetated bars, which are unstable features and are inundated frequently by water during high flows; and densely vegetated areas, which are relatively stable and are inundated only during the largest floods. In this study, the channel width was defined by the width of channels plus the width of unvegetated or sparsely vegetated bars. That is, the width of stable, vegetated areas was subtracted from the total bank-to-bank width to define an active channel width. To a first approximation, this is the width at barfull stage, which probably corresponds to the width associated with the channel-forming flow in braided rivers like the Piave (Thorne *et al.*, 1993). To investigate the results of human impacts at different locations, the study reach was divided into five sub-reaches with homogeneous regulated regimes and morphologies (Table II). The first sub-reach (Longarone–Soverzene) extends from the upstream limit of the study reach, where the river has a strongly braided pattern, to the Soverzene barrage. The Vallone Bellunese, a longitudinal valley, constitutes the second sub-reach (Soverzene–Busche) and extends between

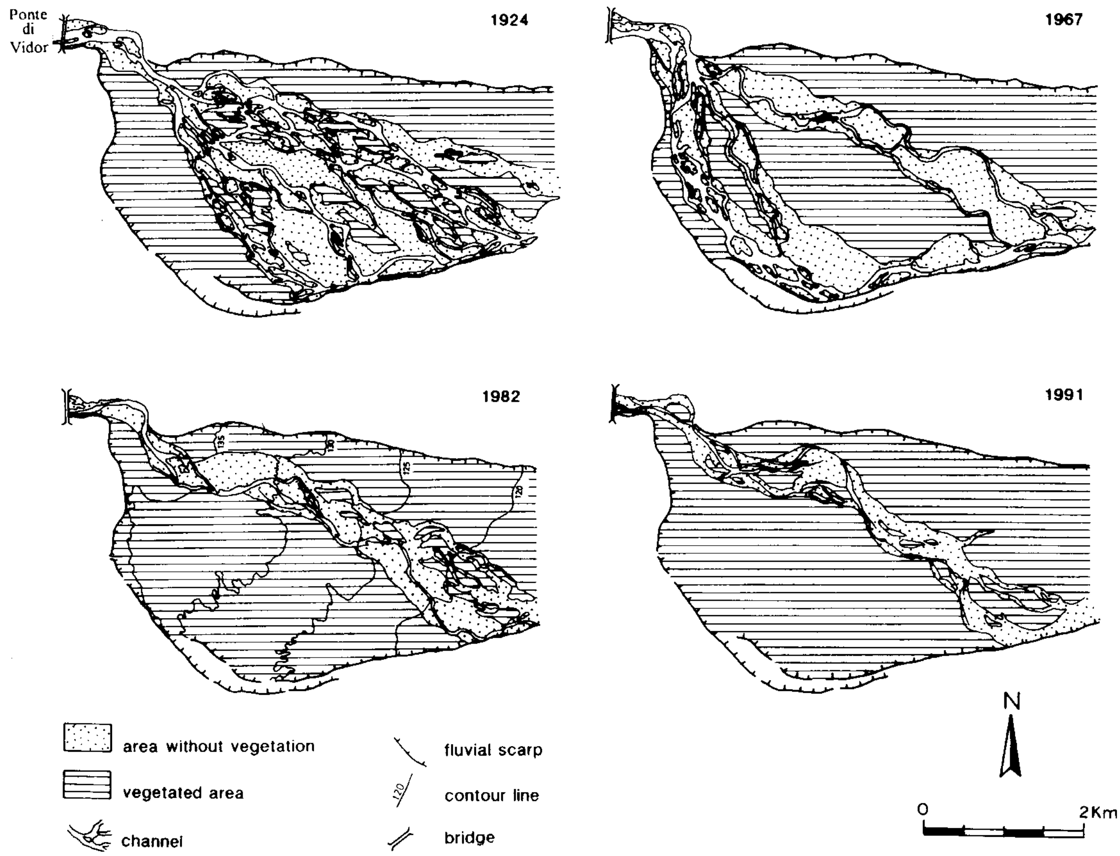

Figure 5. Planform patterns and channel changes for the Piave River at Grave di Ciano (1924–1991)

the Soverzene and Busche barrages. The third reach (Busche–Fener) lies between the Busche and Fener barrages and corresponds to a transverse valley. In the fourth reach (Fener–Nervesa), the river flows across a plain within pre-alpine and sub-alpine relief, extending between the Fener and Nervesa barrages. The fifth reach (Nervesa–Ponte di Piave) lies downstream of Nervesa barrage where the river flows across the Venetian Plain. Average widths of the five sub-reaches and the study reach as a whole during five time periods are listed in Table II. Widths are also expressed as a percentage of the initial width (usually the width in 1894–1910, but 1910–1926 for the Fener–Nervesa reach).

At the beginning of the 20th century, the average width of the study reach had already decreased to 78 per cent of its initial value. Width continued to decrease, although more slowly, until the 1960s, when it was 74 per cent of the initial value. However, rapid narrowing has occurred in the last 30 years, resulting in widths that were only 48 and 35 per cent of the initial value, in 1980–1983 and 1990–1991, respectively.

All five sub-reaches are characterized by a monotonic decrease in channel width as a function of time (Figure 7), although differences in evolutionary trends are evident. During the third time period (1954–1967), width in the two upper reaches (Longarone–Soverzene and Soverzene–Busche) decreased to just 66 per cent of its initial value, while narrowing was less intense in the lower reaches (Fener–Nervesa and Nervesa–Ponte di Piave) which retained 81 and 83 per cent of their initial values, respectively (Table II). However, in the most recent periods these relationships have reversed, with narrowing being more intense in the lower reaches. For example, the 1990–1991 widths of the lower reaches were only 30 per cent (Fener–Nervesa) and 31 per cent (Nervesa–Ponte di Piave) of the initial values, while in the upper reaches widths were 39 per cent (Longarone–Soverzene) and 35 per cent (Soverzene–Busche).

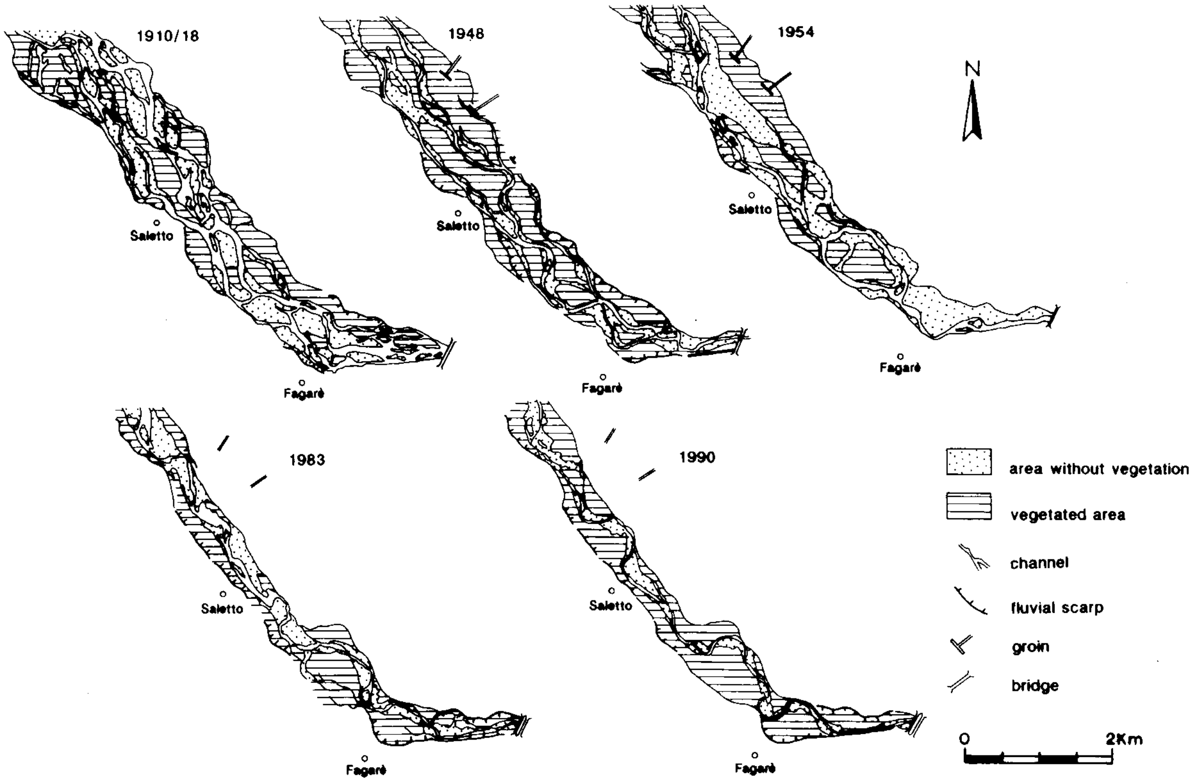

Figure 6. Planform patterns and channel changes for the Piave River at Saletto di Breda during the period 1910/18 to 1990

Table II. Average channel width of the Piave River between Longarone and Ponte di Piave and in five sub-reaches, for five time periods. The figures in parentheses indicate the channel width on different dates as a percentage of the initial width (1894–1910 or, for the Fener-Nervesa reach, 1910–1927)

Reach	Reach length (km)	Number of transects	Channel width (m) 1894–1910	1910–1927	1954–1967	1980–1983	1990–1991
Longarone–Soverzene	8·8	8	635	455 (72%)	420 (66%)	320 (50%)	245 (39%)
Soverzene–Busche	34·8	31	555	445 (80%)	365 (66%)	275 (50%)	195 (35%)
Busche–Fener	19·0	20	465	380 (82%)	330 (71%)	215 (46%)	195 (42%)
Fener–Nervesa	24·7	16	–	775	635 (82%)	355 (46%)	235 (30%)
Nervesa–Ponte di Piave	22·5	19	840	–	695 (83%)	385 (46%)	260 (31%)
Longarone–Ponte di Piave	109·8	94	625	515 (78%)	490 (74%)	310 (48%)	225 (35%)

A quantitative analysis of the spatial distribution of changes of channel width over the study period is shown in Figure 8, which shows the proportion of the initial width (1890–1924) occupied by the present channel (1990–1991). The spatial distribution of width change is somewhat homogeneous and no particular downstream trend is evident. Of the 94 measured transects, 90 exhibit reduced width, two show no variations because the channel is cut into bedrock, and two exhibit widening. In most sections the proportion of the

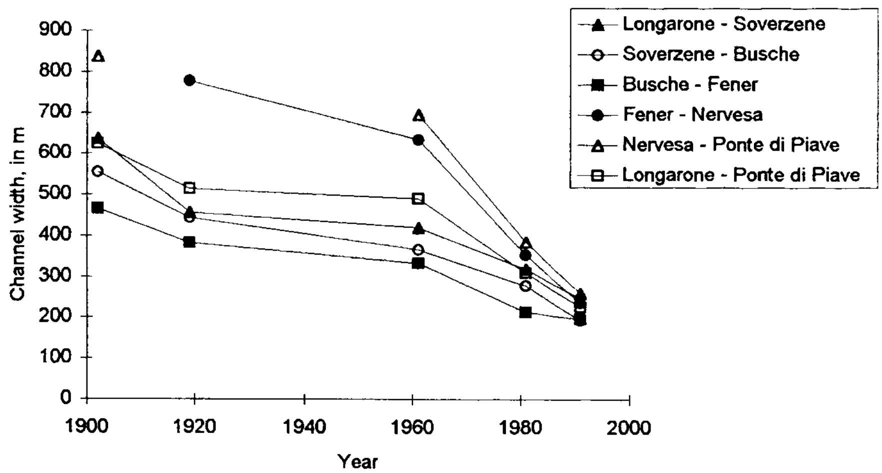

Figure 7. Historical trends of width adjustment in the Piave River for the study reach and five sub-reaches

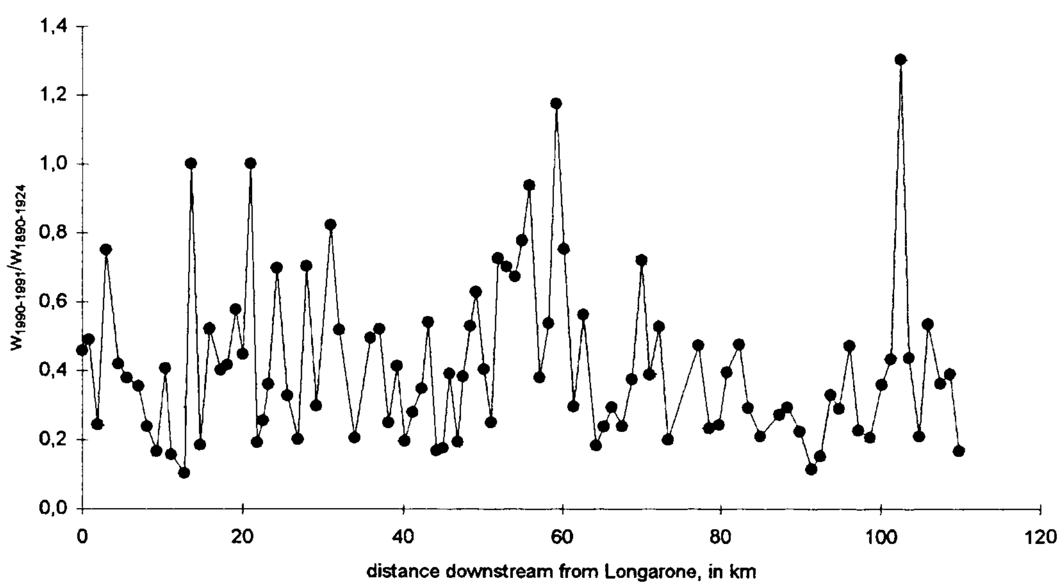

Figure 8. Proportion of the initial width (1890–1924) occupied by the present channel (1990–1991)

initial channel occupied by the present channel ranges between 0·2 and 0·6. It is also clear that width changes are highly variable at the local scale. This is obvious because, although the distance from one transect to the next is only about 1 km on average, width adjustments at adjacent transects differ markedly at many locations.

It is also interesting to note that during the early part of this century channel width was highly variable from one reach to another, mainly as a function of the valley bottom width and the potential for lateral shifting. For instance, initially (1894–1910) the average width for the study reach was 625 m, but sub-reach averages varied from 840 m in the Nervesa–Ponte di Piave reach (where the river flows across the wide Venetian

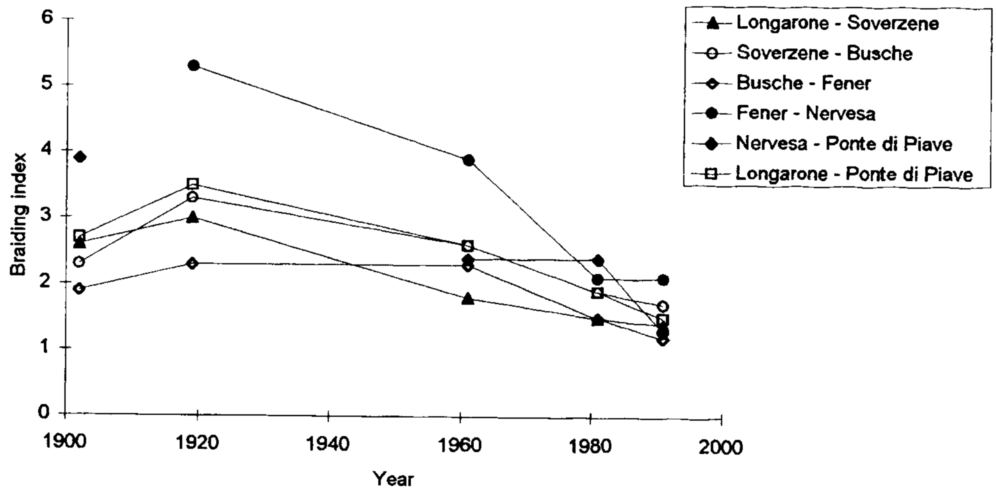

Figure 9. Historical trends in the braiding indices for the Piave River for the study reach and five sub-reaches

Plain), to only 465 m in the Busche–Fener reach (where lateral erosion is constrained by the narrow valley width). However, in the most recent period width is much more homogeneous. For instance, the reach-average channel width in 1990–1991 is 225 m, and sub-reach averages now vary only between 260 m in the Nervesa–Ponte di Piave reach and 195 m in the Soverzene–Busche and the Busche–Fener reaches.

Braiding index

A braiding index (BI) may be used to indicate the intensity of braiding. Several different indices have been developed, including those of Brice (1964), Howard *et al.* (1970), Williams (1978), Ashmore (1991) and Xu Jiongxin (1997). The braiding index proposed by Ashmore (1991) was adopted for this study, because it is a measure of the intensity of flow division which is the essence of braiding (Thorne, 1997). The braiding index for each sub-reach was defined as the mean of the number of channels, or anabranches, containing flow at each of the transects in that sub-reach. The reach-average value was also calculated, as the mean number of channels for all 94 transects. The number of channels at a transect that contain flow is somewhat stage-dependent and, theoretically, the index should be measured at a reference discharge such as mean annual or bankfull flow. Unfortunately, this could not be achieved in the present study. It should be recognized, therefore, that the analysis would have been more objective if all the channels that would be occupied by water during higher in-bank stages could have been considered. Also, the historical BI data set is incomplete because no information was available for the Fener–Nervesa reach for the first period (1894–1910) and for the Nervesa–Ponte di Piave reach for the second period (1910–1926). The results are plotted in Figure 9.

Examination of Figure 9 reveals that there have been significant changes in the braiding index during this century. The temporal trends for the reach-averaged braiding index and all five sub-reaches are similar, displaying a slight increase of the BI during the early 20th century, followed by a slow decrease up until the 1960s. However, since the 1960s there has been a more marked decrease in braiding intensity both at reach scale and in most of the sub-reaches. Extrapolation of recent trends would suggest that braiding intensity may continue to decrease in the immediate future, with BI approaching unity (that is, a single channel configuration) at many locations along the river.

Bed elevation

Information has been derived from the available maps and field observations to estimate the extent of recent changes in river bed elevation. By examining historical maps it has been possible to estimate the

approximate ages and heights of abandoned channels and recent terrace surfaces. These areas, abandoned by the river at various times during the last hundred years, are between 1 and 3 m higher than the present bed. While they are higher than the active floodplain, they cannot strictly be defined as terraces because they can be inundated during larger floods. Therefore, it can be concluded that the river has been incising at a rate of approximately 20 to 70 mm/per year during this century. The highest rates were found immediately downstream of the main barrages.

It is informative to compare these recent rates of bed lowering, which result from morphological response to human intervention, with rates of bed-level change driven by the natural evolution of the river during the Holocene. Holocene geomorphology indicates that between Longarone and Nervesa, incision dominated river evolution, although there were minor phases of aggradation (Vollo, 1942; Pellegrini and Zambrano, 1979), whereas in the downstream reach aggradation prevailed throughout the Holocene. A large fan, with its apex at Nervesa, developed during this period and it has remained active up to historical times. Rates of incision can be estimated for Soverzene–Busche reach, where Holocene terraces have been studied intensively (Surian, 1995). Consideration of the relative elevations of the terraces, floodplain and river suggests an average incision rate of 1 to 4 mm per year for the Piave River during the Holocene.

This preliminary analysis of changes in bed levels highlights the fact that the rate of incision that has occurred in response to human interventions is an order of magnitude greater than the average value during the Holocene. Though recent channel incision along the Piave River has not been as intense as that in other Italian rivers (e.g. Castiglioni and Pellegrini, 1981; Gentili and Pambianchi, 1987; Billi and Rinaldi, 1997), it is still considerable.

DISCUSSION

The history of human engineering and management activities on the Piave River system can be divided into three periods. During the first period, from the 14th century to the end of the 1920s, human impacts on the river were limited and river morphology was in a natural condition, or very close to it. The second period, from the end of the 1920s to the 1950s, witnessed the construction of several dams, diversions and bank protection structures. The installation and operation of dams and diversions altered the water and sediment discharges, while the bank protection structures directly affected the channel morphology and dynamics through restricting the width of the wandering belt. Although these impacts were not particularly severe, they were sufficient to ensure that the river no longer operated as a natural fluvial system.

Since the 1950s, development of the basin's water and natural resources has resulted in a major increase in human impacts through the construction of dams, diversions and bank protection structures, coupled with extensive gravel mining. The flow and sediment regimes of the river have been altered substantially. For example, the mean annual discharge is only about one-third of the natural value, while marked decreases have also taken place in base flows and, probably, channel-forming discharges. However, as dams and diversions are not operated for flood defence, peak flood flows have been little affected. Little information on sediment transport is available, but it is safe to conclude that a considerable reduction of sediment supply and movement through the fluvial system has occurred, due to sediment trapping in the many reservoirs in the drainage basin and along the main stem, and sediment removal by gravel mining. Many groynes and bank structures have been built, constraining the river to maintain a narrower and less mobile channel, reducing bank erosion and, in some reaches, restricting the river to a single, fixed channel.

Morphological response to these changes in the driving variable and boundary characteristics of the channel has been remarkable, particularly during the last 30 to 40 years. Along the entire study reach planform changes, channel narrowing, braiding decrease and channel incision have taken place, although at different rates.

The most obvious changes are that the river has become progressively narrower and less braided. As a result, during this century the average width has decreased to just 35 per cent of its initial value. Width reductions have been particularly intense during the last three decades and recent trends of change suggest that narrowing will continue in the immediate future as the channel adjusts towards a new equilibrium state. Similarly, the degree of braiding has decreased markedly during the second half of this century, with the

reach-averaged braiding index halving from about 3 to about 1·5. The decreasing trend for braiding indices also suggests that further decreases are likely in the immediate future.

Taken together with the results of historical planform analyses, these changes in width and braiding intensity indicate that the overall morphological response of the river to human impacts is to evolve from a typical, braided pattern towards a configuration with a single main channel and a few secondary channels. Several sub-reaches of the Piave River should now be defined as 'wandering' rather than braided in that they display an intermediate configuration between braiding and meandering. This is consistent with morphological changes observed on several rivers of the Po Plain, as observed by Dutto and Maraga (1994). Only in the most downstream sub-reach (Figure 6), where a significant increase of sinuosity has occurred, is it likely that the planform will evolve through the intermediate condition into a truly meandering pattern.

The hypothesis that the observed morphological changes could be driven by climatic change may be dismissed as precipitation records for this century show no significant trend. It is therefore logical to conclude that system response is a consequence of human intervention in flow regime, sediment supply and bank erodibility. On the other hand it must be remembered that channel reductions during the early decades of the century suggest that a narrowing tendency was already established prior to the major phase of river engineering and water resource development.

Schumm (1977) and Petts (1979) have proposed conceptual models to predict the morphological response of channels to changes in the driving variables of water flow and sediment supply. The authors proposed the following relationships:

$$Q^-, Q_{\mathrm{sb}}{}^- \rightarrow w^-, d^{\pm}, (w/d)^-, \lambda^-, p^+, S^{\pm} \qquad \text{(Schumm, 1977)}$$

$$Q^-, Q_{\mathrm{sb}}{}^- \rightarrow w^-, d^{\pm}, A_{\mathrm{b}}{}^-, p^+, S^{\pm} \qquad \text{(Petts, 1979)}$$

where Q = discharge, Q_{sb} = bedload, w = width, d = mean depth, λ = meander wavelength, A_{b} = channel capacity, p = channel sinuosity and S = channel gradient.

The results of this historical analysis demonstrate that the Piave River has exhibited a decrease in the width (w^-), a decrease in the channel capacity ($A_{\mathrm{b}}{}^-$) and an increase in the sinuosity (p^+). While the available data do not allow an accurate estimate of the changes in the mean depth and in the channel gradient, these findings are generally consistent with the morphological response to decreases in flow and bedload expected from theory. The braided Piave River has also experienced a marked decrease in braiding intensity (BI^-), which might be considered as equivalent to a decrease in meander wavelength in a meandering river.

In the case of the Piave River, the magnitude of morphological responses has been very great because there the effects of different human impacts have been, to some degree, additive. For example, the sediment deficit caused by trapping behind dams is amplified by gravel mining conducted downstream of the dams. Similarly, pronounced channel narrowing is the morphological response to the cumulative impacts of flow regulation (particularly a reduction in the channel-forming flow), decreasing bedload, bank protection structures and flow constriction by groynes.

This historical analysis has also demonstrated that the reaction time of this river is short. This is clear from the rapidity with which abrupt changes in channel width and braiding intensity followed the increased human impacts that occurred after the 1950s (Figures 7 and 9). Conversely, the trend of morphological changes suggests that the river is still adjusting towards new equilibrium conditions (Figures 7 and 9), indicating that the 'relaxation time', that is, time taken for the river to attain a new equilibrium state, is not yet complete.

Further remarks can be made with respect to process–form interactions in braided rivers with gravel-bed materials. The similarity between observed channel adjustments and those expected conceptually supports the idea that in braided rivers, as in single-channel ones, there is a strong relationship between morphology and river regime (Ashmore, 1991). Also, the fact that marked morphological response occurred as a result of human impacts that affected only in-bank flows seems to confirm Wolman and Miller's (1960) hypothesis that a stream channel is adjusted and formed by discharges that are relatively frequent, such as bankfull discharge, rather than by large floods. In fact, although some large floods have occurred during this century,

the Piave River channel has progressively narrowed through adjustment to reduction in the channel-forming discharges and associated sediment loads.

CONCLUSIONS

The recent history of the Piave River provides a clear example of how river engineering and natural resource development practices can induce dramatic alterations in river morphology through changing the flow regime, sediment supply and channel boundary characteristics. Analysis of historical maps and aerial photographs has documented decreases in width, braiding intensity and bed elevation, coupled to a planform change from braided to wandering. The magnitude of morphological response was very high. For example, during this century, reach-averaged channel width has decreased to only 35 per cent of the its value at the end of the 19th century, braiding intensity has been halved from about 3·0 to 1·5 and the bed has degraded at 10 times the rate estimated for the Holocene. The magnitude of these changes results from the additive effects of some human interventions and the natural propensity of braided rivers for rapid morphological adjustment. When viewed in light of the record of discharges during the 20th century, the historical analysis indicates that the morphology of the Piave River channel has adjusted to changes in relatively frequent discharges up to and around bankfull, rather than to large floods.

The perspective provided by historical studies like this one is crucial to both understanding the present channel dynamics and predicting future channel evolution. This river system displays a short reaction time, but a longer relaxation time. This is clear because, although it responded almost immediately to increases in human interventions in the 1950s, it is still adjusting to the imposed flow and sediment regimes 40 years later and has not yet reached a new equilibrium state. Improved river management and water resource strategies should take account of the styles and magnitudes of channel change identified in this study and consider steps to avoid or mitigate the adverse aspects of morphological response to future human activities. Specifically, morphological response may affect, to a greater or lesser degree, flood conveyance, channel stability, sediment supply to downstream reaches and the coast, aquifer recharge and aquatic and riparian ecology. Due account must be taken to conserve and protect these important river functions and natural resources and improved understanding of morphological response is a key step towards achieving those goals of river basin management.

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